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Electrical Engineering Department
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FINAL REPORT

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SPACE CHARGE EFFECTS IN CURRENT TRANSPORT

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November 30, 1974

I. LAST YEAR (December 1, 1973 - November 30, 1974)

The effort in this past year has centered exclusively on the noise of current in solids.

A. Noise of Space-Charge-Limited Current in Solids

A third experimental attempt in that many years was made at measuring the noise of space-charge-limited current in a regime in which the mobility of the carriers depends on the field strength. This time, we were finally successful. Measurements of the limiting white noise of space-charge-limited hole current in silicon were made at dc voltages where the hole mobility becomes field-dependent. The surprising result was established that the hole temperature is equal to the lattice temperature at 110K within 10% at voltages where the deviations from constant mobility reach 50%. This result contradicts accepted theories relating carrier temperature to field-dependent mobility. Several laboratories are now tooling up to confirm this remarkable fact and investigate it further. A publication of this work is in press:

> "Therman Equilibrium Noise of Space-Charge-Limited Current in Silicon for Holes with Field-Dependent Mobility," by J.L. Tandon, H.R. Bilger and M-A. Nicolet, Solid-State Electronics (in press).

B. Noise in Implanted Layers

This effort has continued throughout the year, with the collaboration of H.R. Bilger (Oklahoma State University). The low-frequency noise spectra of partially annealed boron-implanted silicon resistors with various geometries have been measured. The implantation energies were 50, 80 and 110 keV and the doses were 2.5×10^{12} cm^{-2}, 1.0×10^{13} cm^{-2} and 1.0×10^{14} cm^{-2}. The spectra exhibit thermal noise and f^{-n} (excess) noise exclusively. Investigations indicate that the contacts from the implanted layer to the electrode generally contribute small amounts to the total excess noise observed. The excess noise exhibits a strong inverse dependence on the sheet resistance of the layers, while the dependence on substrate bias, implantation energy, and on temperature is relatively weak. A discussion of the results show that the data are compatible with a volume effect. Such an interpretation goes very much against accepted thinking. Noise measurements on implanted layers, produced under carefully controlled conditions, show promise as a tool to investigate excess noise. The following paper has been completed and published on the subject:

"Excess Noise Measurements in Ion-Implanted Silicon Resistors," H.R. Bilger, J.L. Tandon and M-A. Nicolet, Solid-State Electronics 17, 599 (1974).

The project will continue under an NSF grant approved this June for another 1 1/2 year duration.

II. OVERALL VIEW OF THE GRANT AND ITS ACCOMPLISHMENTS

This grant was initiated on April 1, 1968 under the auspices of NASA's Electronics Research Center, was transferred to the Langley Research Center upon the Electronics Research Center's closure in 1970, and was extended in 1972 without additional funds until November 30, 1974. The total sums approved and disbursed are:

$22,200	April 1, 1968
18,000	April 1, 1969
27,000	April 1, 1969 (step funding)
30,000.	December 1, 1969
$97,200	

Over the total period of 6-2/3 years, the support amounted to an average of $14,600/yr (including overhead). This money has supported (in part) the work of the following persons:

*Bilger, H.R. (Oklahoma State University)
Gorris, R.
Lee, D.H.
Nicolet, M-A.
Taynai, J.D.
*Worch, R.P. (Oklahoma State University)

Permanent testimony of their activities is contained in the following openly accessible theses, report and articles:

*Visiting participants at Caltech

Theses:

1. D.H. Lee (California Institute of Technology, November, 1969)
"Double Injection: High Frequency Noise and Temperature Dependence"

2. J.D. Taynai (California Institute of Technology, November, 1969)
"Properties of α-Monochimic Selenium"

3. Q.T. Vu (California Institute of Technology, April 1970)
"Space-Charge-Limited Current in Fast Neutron Irradiated Silicon"

4. P.R. Worch (Oklahoma State University, Mayer 1970)
"An experimental Investigation of Generation-Recombination Noise in Double-Injection Diodes"

Report: "A Simple Versatile Thermostat for Small Objects and the Temperature Range of $100^{o}K$ to $400^{o}K$," Scientific and Technical Aerospace Reports (STAR) 8, No. 7, p. 1252 (1970), (accession No. N70-18959).

Publications:

1. "Noise Measurements on a Double-Injection Silicon Diode," D.H. Lee, H.R. Bilger and M-A. Nicolet, JPL Space Program Summary 37-52, Vol. III (1968).

2. "Noise and Equivalent Circuit of Double Injection," H.R. Bilger, D.H. Lee and M-A. Nicolet, J. Appl. Phys. 13, 5913 (1968).

3. "Thermal Noise in Double Injection," D.H. Lee and M-A. Nicolet, Phys. Rev. 184, 806 (1969).

4. "Effect of 14 MeV Neutrons on Space-Charge-Limited Current of Electrons in High Purity Silicon," Q.T. Vu and M-A. Nicolet, IEEE Trans. NS-16, 69 (1969).

5. "Generation-Recombination Noise in Double-Injection Diodes," H.R. Bilger, P.R. Worch, L.L. Lee and M-A. Nicolet, Solid-State Elec. 12, 849 (1969).

6. "A Flexible Simple Thermostate for Small Objects and the Range of 100 to 400 K," H.R. Bilger and M-A. Nicolet, Rev. Sci. Instr. 41, 366 (1970).

7. "The Density of α-Monoclinic Selenium," J.D. Taynai and M-A. Nicolet, J. Phys. Chem. Solids 31, 1651 (1970).

8. "Thermal Noise in Single and Double Injection Devices," M-A. Nicolet, Solid-State Elec. 14, 377 (1971).

9. "Electron Trapping in Neutron Irradiated Silicon Studied by Space-Charge-Limited Current," Q.T. Vu and M-A. Nicolet, J. Appl. Phys. 43, 2755 (1972).

10. "Noise of Hot Holes in Space-Charge-Limited Germanium Diodes," M-A. Nicolet, H.R. Bilger and A. Shumka, Solid-State Elec. 14, 667 (1971).

11. "Noise of an Injected Plasma in Silicon," H.R. Bilger and M-A. Nicolet, Proc. Intl. Conf. Noise on Active Semicon. Devices, Toulouse, September 1971.

12. "Backscattering Microscopy: New Campaigns for a Veteran Technique," M-A. Nicolet, J.W. Mayer and I.V. Mitchell, Science 177, 841 (1972).

13. "Thermal Noise Measurements on Space-Charge-Limited Hole Current in Silicon," J. Golder, M-A. Nicolet and A. Shumka, Solid-State Elec. 16, 581 (1973).

14. "Thermal Noise Calculation of Single-Carrier Space-Charge-Limited Current in a Non-Insulating Solid," M-A. Nicolet and J. Golder, Phys. Stat. Sol.(a) 15, 565 (1973).

15. "Noise of Space-Charge-Limited Current in Solids is Thermal," J. Golder, M-A. Nicolet and A. Shumka, Solid-State Elec. 16, 1151 (1973).

16. "Experimental Test of $S_V = 4kT(V/I)$ for Space-Charge-Limited Current of Holes in Silicon," M-A. Nicolet and J. Golder, Phys. Stat. Sol. (a) 17, K49 (1973).

The main thrust of the grant has been directed at the clarification of the noise properties of space-charge-limited current (single injection) and of two-carrier current (double injection) in solids. At the time of the inception of the grant, the theoretical ideas on the subject were speculative, and the experimental data available were fragmantory, and preliminary at best. Today, and due mainly to the efforts undertaken under this grant (and those that followed it later), the subject has now reached a level of accurate quantitative knowledge and understanding.

In addition to this body of knowledge which has been gatered on the subject of noise in the two specific types of currents in solids, the results have lead to another, unsuspected development. As the understanding of these special cases progressed, it became obvious that any theoretical treatment which would explain the observed noise behavior of these currents had to have much broader validity, simply because single- and double injection currents are nonlinear in nature. The concepts which were being developed would be applicable to many other nonlinear systems as well. In the long run, the most significant contribution of this grant may thus lie in the conceptual manner in which noise phenomena will be treated theoretically in the future. The matter has raised enough general interest that we have been asked to write a review paper on the subject. This paper has just been completed and constitutes the most fitting final report for this grant. A copy is included. It will appear as:

> "Noise in Single and Double Injection Currents in Solids," M-A. Nicolet, H.R. Bilger and R.J.J. Zijlstra, Physica Status Solidi(b) (1975).

In addition to noise, work under this grant also covered studies of trapping and radiation damage in space-charge-limited current in solids. It was found that devices which are based on this type of current flow are not as insensitive to radiation as had been predicted on the grounds that carrier lifetime in majority-carrier devices is irrelevant. Trapping, not recombination, is the process which degrades such devices, and trapping can degrade with dose as ruinously as lifetime does in minority-carrier devices.

There is one promise which space-charge-limited currents in solids have not betrayed: these currents can flow through a solid from $4.2^{O}K$ to a temperature whose maximum is limited solely by the free carrier concentration of a bulk. We have observed them in silicon from $4.2^{O}K$ to $50^{O}C$ ($323^{O}K$), which is a factor of almost 80 (!) in absolute temperature variation. In materials with a bandgap wider than silicon, the maximum operation temperature must go up very rapidly.

Space-charge-limiting current may indeed be the best mode of current flow with which to design high-temperature devices. A search for the most promising host material, and experimentation with it, was to be the last step in the long-range program which this laboratory had launched in 1964 with the goal of clarifying the properties and potential of space-charge-limited currents in solids. It is a pitty that NASA's support of the project was terminated prematurely, not only because the final phase of this long-range program is now in limbo, but because this may well have left the most promising property of these currents still unexplored.

In spite of this deficiency, the project as such has been a success. At times, the grant has been marred by administrative problems and difficulties. But the final years of very smooth (yet doomed) existence provided a sheltered climate in which the efficiency and productivity have risen to remarkable levels.

Noise...

IN SINGLE AND DOUBLE INJECTION CURRENTS IN SOLIDS

by

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This review discusses the developments over the last ten to twelve years which brought the subject of noise in single and double injection from its hesitant beginning to the present stage of accurate factual knowledge. The text discusses only the most conclusive results in detail, but an attempt has been made to provide a complete bibliography of all published work in the field. Conflicting findings and opinions are examined in the light of the present understanding of the subject, so that the interested reader will have access to the literature with a critical view and an appreciation of the historical context.

M-A. Nicolet

H.R. Bilger

R.J.J. Zijlstra

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VI. SUMMARY, CONCLUSIONS AND OUTLOOK

It is the advent of very high purity silicon and germanium single crystals which promoted progress in the field of noise in nonlinear devices. With these materials, it is possible to make devices for which the simple models of single and double injection hold very closely. Accurate measurements on such devices have established the following facts.

Noise in single injection is thermal. The theory shows that for single carrier space-charged limited current,

$$S_v = 4kT \cdot 2\mathrm{Re}(Z) \quad . \tag{VI.1}$$

Experiments have confirmed this expression to within 5%. This result expands the quantitative description of thermal noise to nonlinear devices. In their two classical paper, Johnson(J1) showed experimentally and Nyquist(N11) derived theoretically that at thermal equilibrium and for a linear device, the thermal fluctuation processes lead to a noise of

$$S_v = 4kT \cdot \mathrm{Re}(Z) \quad . \tag{VI.2}$$

We now find that for a macroscopically nonlinear system such as single-carrier space-charged-limited current, these same processes lead to an observable noise which is twice as large. There is clearly a need for a careful distinction between the

two cases. We therefore propose that henceforth the name "Nyquist noise" be used only in connection with noise in linear systems at thermodynamic equilibrium. On the other hand, the terms "thermal noise" or "scattering noise" cover nonthermodynamic equilibrium cases as well and therefore apply to noise of single carrier space-charge limited current.

The studies of noise in double injection have brought to light yet another form of thermal noise in nonlinear systems. Indeed, for frequencies large compared to the characteristic time constants of recombination, a double injection diode possesses purely thermal noise of a value

$$S_v = 4kT \cdot \mathrm{Re}(Z) \quad . \tag{VI.3}$$

The validity of this formula has also been established within < 5% error. In contrast to the result for single injection, this equation is the same as for Nyquist noise, although double injection can have a nonlinear characteristic which is also $I \propto V^2$, as for single injection. This observation leads to two conclusions: (i) thermal noise in nonlinear devices can have different forms, depending on the specific nature of the device, and (ii) the dc characteristics of the device alone is insufficient to establish the formal representation of this noise.

Equations VI.1 and VI.3 are both of the form

$$S_v = 4kT \cdot \alpha\mathrm{Re}(Z) \quad ,$$

where α is a number of the order of unity. It has been proposed that this result is very general.(S4) Some aspects of this idea are presently investigated further.(V21) It would be desirable to find additional experimental and theoretical support to this idea from other basic modes of nonlinear current flow, if such modes can be conceived and realized.

At frequencies small compared to the recombination time constants, noise in double injection is dominated by gr processes. Again the theoretical prediction and the experimental results agree very well. This work extends the conventional concept of gr noise to nonlinear devices. The extension is not as notable as for thermal noise in single injection however, because gr noise is normally visible only under nonthermal equilibrium conditions. Again it is found that the nature of the device significantly affects the observed noise and its functional dependence on the current. The spectral density in the semiconductor and in the insulator regime are quantitatively different, but the frequency dependence which is characteristic of gr noise is found in both cases: a plateau at low frequencies whose value increases strongly with the dc current, and a sharply decreasing spectrum which falls off approximately as $1/\omega^2$ at frequencies above the characteristic recombination-generation time constant.

In addition to this body of new factual knowledge which was obtained, the study of noise in single and double injection has exerted a strong influence on the theoretical development in the field. The impact was not so much along the lines of

basic physical processes of fluctuations, since no new noise-generating processes have been uncovered. Rather, interest has been directed towards understanding the effect of a macroscopic nonlinearity of the device on the way the microscopic fluctuations in each volume element add up to the actually observed noise of the whole device. The new method of calculating noise by the impedance-field method devised by Shockley et al.(S9), and which had remained unused so far has been shown to be very valuable for such investigations. In the case of single injection an exhaustive treatment has been given by this technique and has confirmed all results previously established with the more traditional Langevin method of noise calculation.(R3)

From a more general perspective, the understanding of noise in macroscopically nonlinear electrical devices, such as single or double injection diodes, has significance to the theory of fluctuations in nonlinear system of other kinds as well. The methods and concept developed for these particular devices will retain their validity generally, as long as the macroscopic nonlinearities do not affect the stochastic properties at the microscopic level. In the long run, these generally valid ideas may well turn out to be more prominent contributions to the field of knowledge than the specific facts elucidated for the particular devices discussed in this review.

Another contribution of the work on single and double injection has been the formulation of questions whose answers

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are still outstanding. Foremost among these is the extension of the impedance-field method to two carrier systems. As Shockley et al. formulated it, the method applies only to devices with a single carrier type. This restriction is unnecessary, because it has been shown very recently that the Langevin and the impedance-field method of noise calculation are equivalent techniques.[M3,T5] That result also must be listed among the major accomplishments promoted by work on noise in single and double injection. The lines along which the impedance-field method has to be generalized for noise calculations in two carrier systems are fairly clear. The actual formulation of rules and the execution of first calculations, however, have yet to be done. This work is in progress and results are expected soon. The development of the impedance field method of noise calculation is a prominent event. By design, the method is very well suited for noise calculations in complicated structures where simplified assumptions have to be made on physical rather than analytical grounds. It can be anticipated that the method will gain increasing acceptance in the future. The impedance-field method has also been used very recently to prove that in general the salami method of noise calculation is incorrect.[T4]

The main deficiency of the work carried out so far both experimentally and theoretically is the neglect of diffusion. As long as diffusion is absent, the results for single and double injection cannot be related in a continuous fashion to those derived for pn junctions. But this bridge does of

course exist, since a pn junction can be regarded as a double injection diode with vanishing base width. A similar relationship exists between the bipolar transistor and single injection. The analytical difficulties encountered in the theoretical treatment of this problem, for example by the Langevin method, are substantial. It is hoped that some effort will be undertaken nevertheless, because in the present absence of any information, no statements can be made as to the validity or the seriousness of neglecting diffusion. Other areas worthy of exploration are the extension of noise measurements towards higher frequencies in double injection, and a clarification of the relationship between single injection and ohmic contacts and their noise. The experimental difficulties in each case are severe.

A field of work in which there is presently much activity is that of single injection with hot carriers. The great advantage of single-carrier space-charge-limited current for the study of hot carriers is that the carrier distribution can be maintained in a stationary state without exceeding power limitations. It is likely that new information on the behavior of electrons and holes at very high field strengths will be obtained from noise studies in single injection structures. Specifically, it will be very desirable to independently confirm the very recent observation that holes in silicon can exhibit strong nonlinearity in the velocity-field relationship while not exhibiting noticeable heating over the lattice temperature.[T1]

To be trustworthy, such measurements require great care not only in the data collection, but also in the preparation of a sample and its characterization. Not enough attention has been given to the sample in the past. As the sophistication of the field increases, so does the complexity of the device and the difficulty of its preparation. The probability that a given device possesses a flaw increases accordingly. It is unavoidable that further experimental progress in the field of noise in nonlinear devices will depend increasingly on the time and care an investigator is willing to devote to the preparation and the analysis of the samples he uses in the measurements.

ACKNOWLEDGEMENTS

During the many months of its preparation, this review has benefited of some financial assistance by the National Aeronautics and Space Administration, by the Caltech President's Fund, and by the National Science Foundation in the U.S., as well as by the Dutch Stichting FOM. It is with gratitude that the authors acknowledge this support without which this review, and indeed some of its content, would not now exist.

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(review paper)